SMOKE PRODUCTION FROM LARGE OIL POOL FIRES

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ABSTRACT

This study is motivated by a desire to understand the near and far field effects of large fires, and in particular the current need to understand the consequences of burning large pools of oil as a means of responding to a spill emergency. A concern related to burning oil is that the smoke particulate content of the plume may be a health hazard. The smoke yield (fraction of the burned fuel that is emitted as smoke particulate) was measured for crude oils in laboratory and mesoscale field experiments conducted in the United States and Japan. Scaling of smoke yield from laboratory to large scale fires is based on results from pool fire experiments from 0.085 m to 17.2 m in diameter. An important finding of this study is that smoke yield varies approximately by a factor of two between laboratory tests (6 percent smoke yield) and larger diameter fires conducted out-of-doors (13 percent smoke yield). The large laboratory experiments conducted in Japan, showed that a pool fire of 2 m in diameter produced nominally the same smoke yield as the largest fires tested.

INTRODUCTION

Response to oil spills includes consideration of oil containment, recovery, disposal and the logistics of delivering adequate response equipment quickly to the spill site. In-situ burning of spilled oil has distinct advantages over other countermeasures. It offers the potential to convert rapidly large quantities of oil into its primary combustion products, carbon dioxide and water, with a small percentage of other unburned and residue byproducts. Burning of spilled oil from the water surface reduces the chances of shoreline contamination and damage to biota by removing the oil from the water surface

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ɪefore it spreads and moves. In-situ burning requires minimal equipment and less labor han other techniques. It can be applied in areas where many other methods cannot due ɔ lack of response infra-structure and/or lack of alternatives. Oil spills amongst ice and ɪn ice are examples of situations where practical alternatives to burning are very limited. Because nominally 90 percent of the oil is converted to gaseous products of combustion ɪy burning, the need for physical collection, storage, and transport of recovered fluids is educed to the few percent of the original spill volume that remains as residue.

Burning oil spills produces a visible smoke plume. Normally the smoke is dispersed and ettles to the ground over tens to hundreds of kilometers downwind from the source. The hemical content of this plume and in particular the particulate content may be a concern or public health. As input to the analysis of smoke plume dispersion, smoke yields were neasured for crude oils in laboratory and mesoscale field experiments conducted in the Jnited States and Japan.

BACKGROUND

The National Institute of Standards and Technology (NIST) has carried out a program of oil spill burning research since 1985. This program was launched based upon the success of tests conducted in 1983 at the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility in Leonardo, New Jersey [1,2]. The research program at NIST sponsored by the Minerals Management Service (MMS), part of the U.S. Department of the Interior, was designed to study how burning large oil spills would affect air quality by quantifying the products of combustion and developing methods to predict the downwind smoke particulate deposition.

Initially the burning process was studied at two pool diameters, 0.6 m and 1.2 m. Measurements showed that about 10 percent of the crude oil was converted to smoke in the combustion process [3,4]. Smoke emission was measured during the burning of oil layers thin enough to cause boiling in the supporting water layer. Under these conditions smoke emission was reduced compared to burning of thicker layers. The smoke yield was found to decrease by more than a factor of two when the initial oil layer thickness was decreased from 10 mm to 2 mm. The 2 mm depth was thus used in further testing [5].

In 1990, development of new instrumentation to perform measurements of combustion characteristics and smoke emissions from large crude oil fires outside of the laboratory began [6]. The next year [7,8,9] measurements were made with the newly developed instrumentation on large oil fires from 3 meters in diameter at the Fire Research Institute in Japan, to 17.2 meters in diameter (mesoscale) at both the Navy Fire Fighter Training facility in Norfolk, Virginia and the U.S. Coast Guard's Fire and Safety Test Detachment in Mobile, Alabama. Analysis of the data from the 1991 mesoscale experiments is reported in [10], along with additional laboratory measurements of smoke yield which were performed with the identical oil used in the mesoscale experiments to examine the effect of scaling.

EXPERIMENTAL FACILITIES

At NIST, two major facilities were used to measure the smoke yield from cru oil pool fires ranging in size from 0.085 m to 0.6 m in diameter. The smallest fire 0.085 m diameter, were conducted in the Cone Calorimeter. The Cone Calorimeter more formally known as Standard Test Method for Heat and Visible Smoke Release Rat for Materials and Products Using an Oxygen Consumption Calorimeter [11]. A larg calorimeter apparatus capable of accommodating samples up to 0.6 m in diameter wi an instrumented exhaust hood, was used to provide additional NIST laboratory data the effect of fire diameter on smoke yield from crude oil fires. In both apparatus sampl drawn from the exhaust hood duct were used to quantify the amount of each maj combustion product generated per kilogram of crude oil burned.

The relatively small, 0.6 m diameter, fires were conducive to measuring fire character tics under controlled conditions, but are too small to provide an adequate test measurement equipment being developed for field use. Through the cooperation of t Fire Research Institute (FRI) in Tokyo, Japan, joint studies of crude oil burni characteristics were conducted. FRI maintains a fire test facility in which crude oil po up to 3 m in diameter are burned, with all of the combustion products collected in a lar hood system. A 2 m diameter crude oil fire was burned in the 24 m x 24 m x 20 m hi test hall. This facility could accommodate fires that are large enough so that sampli packages designed for mesoscale tests could be evaluated. The exhaust system for t building was instrumented so that measurements similar to those performed in the NI facility could be made by effectively using the entire FRI test building as a smoke coll tion hood.

The mesoscale burns of crude oil were carried out under the direction of NIST at t United States Coast Guard Fire and Safety Test Detachment facility on Little Sand Isla in Mobile Bay Alabama. The burns were conducted in a nominal 15 m square steel p constructed specifically for oil burning on water. The pan is described fully in [1 Three primary burn areas were used in the series. The partial pan areas were achie by partitioning a corner of the inner pan with 0.14 m by 0.14 m timbers covered w sheet steel. Plywood skirts 0.3 m deep were attached to the timbers below the wa surface to prevent the oil from flowing under the timbers. An effective diameter calculated for each of the rectangular burn areas. The effective diameter is the diame of a circle with the same area as the rectangular burn area used. Effective diameters the three size burns were 6.88 m, 12.0 m, and 17.2 m.

ELEMENTAL ANALYSIS OF CRUDE OILS

Two types of oil were used in this study. A Louisiana crude oil and a Murl crude oil. Samples of each oil type were analyzed for composition by a commer laboratory. Two separate analyses were performed by the same laboratory for each and the average results are presented in table 1.

Table 1. Elemental analysis of Louisiana and Murban crude oils

Element	Louisiana Oil (mass fraction)	Murban Oil (mass fraction)	Repeatability
Carbon	0.862	0.848	± 0.2 %
Hydrogen	0.134	0.141	± 1.6 %
Sulfur	0.000	0.008	± 4.0 %

ɴOKE YIELD MEASUREMENTS

The quantity of smoke produced from a fire may be expressed as a smoke yield hich is defined as the mass of smoke particulate produced from burning a unit mass of el. Techniques now exist to measure smoke yield both in the laboratory and in the :ld.

ıree methods of determining smoke yield from pool fires have been used in laboratory periments in which all of the combustion products can be collected in a hood over the e; 1) the direct particulate flux method, 2) the carbon ratio method, and 3) the indirect ;ht extinction method. These methods are discussed in detail by Mulholland et. al [12] ıd summarized below. The direct particulate flux method for determining smoke yield volved filter extraction of particulate from a portion of known and well mixed hood haust flow and using that measurement to determine the total particulate flux. In this ıse, smoke yield is the ratio of the total particulate flux to the mass loss rate of the ırning fuel. The mass of smoke particulate, m_s, collected on a filter, the mass loss of e fuel burned, m_f, and the ratio of the mass flow of air through the exhaust stack to the ass flow through the filter sample, ϕ, are measured. The smoke yield calculated by the ıx method is termed ε_1, and is given by the expression

$$\varepsilon_1 = (m_s/m_f)\ \phi \tag{1}$$

he carbon ratio method is based on a partial carbon balance, and is the only smoke yield easurement method that can be used both in the laboratory and in the field because it ɔes not require measurement or knowledge of the total combustion product flow. In this ethod, smoke yield is expressed as the product of the measured fraction of carbon in the ıel, f_c, and the ratio of the measured carbon in the form of smoke particulate to the total ırbon mass in the combustion products (CO_2, CO, and smoke aerosols), Y_s. Smoke ıeld by carbon ratio method is denoted by ε_2 and given by

$$\varepsilon_2 = f_c \, Y_s \tag{2}$$

The application of the carbon ratio method to smoke yield measurements in the field is limited to sampling from regions of the plume close to the source where there is confidence that both the smoke particulate and gaseous combustion products have been transported together from the combustion zone and their concentrations have been equally diluted by entrained air.

A smoke yield measurement that is completely independent of particulate collection on filters is the light extinction method. The indirect light extinction method uses measurements of light beam attenuation across the hood exhaust stack to determine the particulate loading in the flow. This value is divided by the known mass loss rate of the fuel to determine the smoke yield. This method is based on determining the mass concentration of smoke particulates in a known flow rate of combustion products by measurement of visible light attenuation over a known path length. In this study smoke attenuation measurements were made with a laser photometer. The design of the instrument is described by Babrauskas and Mulholland in reference [13]. The light source used in the instrument is a helium-neon laser with a low flow rate air purge to avoid deposition of soot on the optics. Detector electronics processed the signal and the output was recorded directly in units of extinction coefficient, k (m^{-1}). Calibration was accomplished with known neutral density filters introduced in the beam.

In the field, the carbon ratio method was used. Smoke was drawn by a battery operated pump through a pre-weighed filter which collected the particulates. The clean gas passed through the pump to a set of micrometer adjusted flow control valves which metered and diverted a portion of the gas flow to a 5 liter sample collection bag. A radio controlled switch was used to start and stop the pump remotely as the sampling package was carried into and removed from the fire plume [8]. The filter samples were weighed on a precision balance after the burn, and the concentrations of CO_2 and CO in the sample collection bag were determined using a gas chromatograph. In the mesoscale burns, the sampling package was suspended below a tethered miniblimp and was manually maneuvered from the ground and held in the smoke plume downwind of the fire.

RESULTS

Smoke yield measurements for the two crude oils, Murban and Louisiana, using all three measurement methods in laboratory experiments, are presented in table 2. It can be seen that there is excellent agreement between all three methods in the Cone Calorimeter. The largest variation between the three methods is 6%. This is most likely because the Cone Calorimeter produces a highly controlled and reproducible fire environment. The smoke yield from the Louisiana crude oil is approximately 20% greater than the yield from the Murban crude oil.

Smoke yields from the mesoscale burns, which used Louisiana crude, are given in table 3 and smoke yields calculated by the carbon ratio method for all scale are shown in figure 1. For the mesoscale burns an estimation of the uncertainty of the smoke yield was determined. The uncertainty interval was based on the accuracy of the balance, the chromatograph and the flow measurements. The uncertainty is shown as error bars in figure 1. From figure 1 it can be seen that smoke yield is dependent on scale. The yield is lower for smaller diameter fires and appears to reach a plateau of approximately 0.13 for fires with diameters above 2 m. In small diameter fires the air which is entrained around the fire perimeter more readily mixes with the fuel resulting in more complete combustion and a lower smoke yield. The smoke yield from burn 5/17 is distinctly lower than the yields from the other burns. An examination of the start time, sample duration, wind speed and burning rate did not provide an explanation for the low result.

Table 2. Laboratory measurements of smoke yield from crude oil fires

		Fuel Type	Flux Method ε_1	Carbon Ratio Method ε_2	Light Extinction Method ε_3
Cone Calorimeter D= 0.085 m	1	Murban	0.053	0.053	0.053
	2	Murban	0.052	0.052	0.049
	3	Murban	0.057	0.057	0.054
	4	Murban	0.054	0.056	0.052
	5	Louisiana	0.063	0.067	0.060
	6	Louisiana	0.058	0.062	0.061
	7	Louisiana	0.063	0.068	0.062
Large Calorimeter D = 0.6 m	1	Murban	0.093	0.080	0.067
	2	Murban	0.093	0.077	0.082
	3	Murban	0.090	0.082	0.063
FRI, Japan D = 2.0 m	1	Murban	0.134	0.139	0.149
	2	Murban	0.128	0.137	0.150

Table 3. Smoke yield from mesoscale burns

Mesoscale Burn No.	Effective Diameter (m)	Smoke Yield	Uncertainty Interval
4/16/91	6.88	0.137	0.123 - 0.152
5/17/91	6.88	0.079	0.070 - 0.085
6/3/91	12.0	0.121	0.109 - 0.135
6/5/91	17.2	0.127	0.109 - 0.154

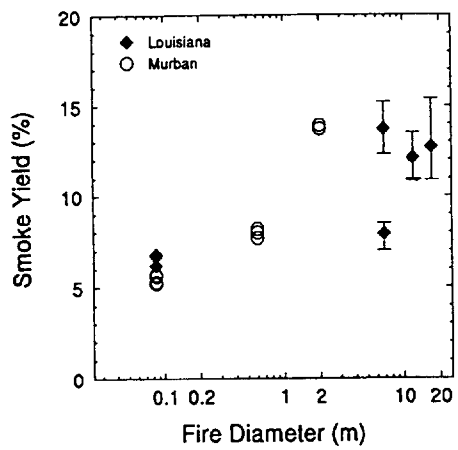

figure 1. Smoke Yield %

CONCLUSIONS

The carbon ratio method of smoke yield, which may be used in the field as well as in the laboratory, was shown to agree within 15 percent with the direct particulate flux method and indirect light extinction method in laboratory experiments. The carbon ratio method was used in field measurements of smoke yield from large pan crude oil fires. The smoke particulate yield from these large fires was found to be 13 percent of the mass of the oil burned. Experiments showed that 2 m diameter fires in the laboratory had nominally the same smoke yield as larger 6.88 m to 17.2 m effective diameter pan fires conducted out-of doors.

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